MODELING OF LOW VOLTAGE SWITCHGEAR AND CONTROLGEAR ASSEMBLIES USING COMPUTATIONAL FLUID DYNAMICS

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Abstract- Low voltage switchgears and controlgear assemblies contain multiple conductors and electrical devices ensuring current distribution and protection of an installation. During operation, heat is dissipated by conductors and electrical devices leading to temperature rises in the panel. For different reasons, internal temperature must be limited and controlled. Hence, the target is to determine innovative cooling solutions with quantified efficiency. Designing and testing each variation is a costly and time consuming process. This challenge is tackled by developing a simulation model to predict temperatures and airflow characteristics for different enclosure design variants. Yet before assessing any new design's efficiency, the simulation model must be validated. The present study introduces the methodology used to model the complete assembly system, from 3D simplifications to specific simulation parameter settings, to achieve this validation step. To ensure a reliable validation, two specific types of switchgears are studied: one with a hermetic enclosure and another one with a ventilated enclosure. Three important aspects are considered during the design of the simulation model. The first aspect is the high scale variations within the object considered. Modeling thin walls including scales from the meter (height of the enclosure) down to the millimeter (thickness of the wall) poses severe meshing challenges. The shell conduction method is applied to model thin sections. The second aspect relates to the air density model. An incompressible ideal gas model has been used to model buoyancy and gravity forces driving natural convection. The third important aspect is radiation. The role of radiative heat transfer is studied using a surface-to-surface radiation model.

Index Terms- Low voltage switchgear; natural convection; shell conduction; radiation; thermal management

I. INTRODUCTION

Low voltage switchgears are used in a wide variety of environments for power distribution, such as hospitals, commercial buildings and data centers as shown in Fig.1. Switchgear assemblies are equipped with massive copper busbars conducting and distributing current across e.g. withdrawable units equipped with contactors and motor protection breakers responsible for ensuring reliable and safe power supply as explained in Eaton product manual [1]. When currents with magnitudes exceeding several thousands of amperes are conducted through the busbars, a large amount of heat is dissipated by the conductors and the protective components.

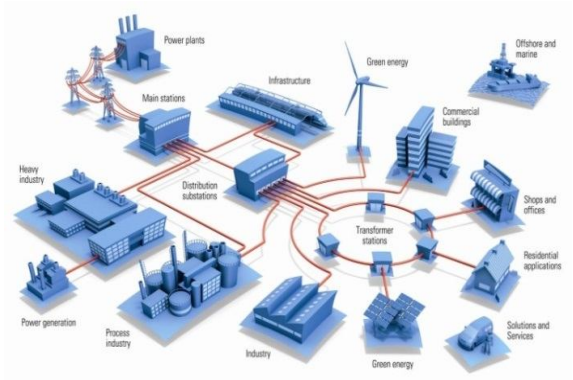


Fig 1. Examples of low voltage switchgear assembly applications

This temperature rise must be controlled for two main reasons : firstly, temperature limits are set by international IEC standards for low voltage; secondly, electronic components located within the protective devices are sensitive to certain temperature levels. Thermal management is therefore of utmost importance in the design of switchgear enclosures. Computational Fluid Dynamics (CFD) allows engineers to assess and compare several configurations avoiding unnecessary prototyping and experimental tests, thereby resulting in cost and time savings. The benefit of simulation towards testing is mentioned in literature [3]. Feroz et.al. extensively studied similar systems of air-cooled high powered telecommunication cabinets [2]. Limin et.al. analyzed temperature variation in a refrigeration cabinet to understand the thermal scenarios [4]. Mahdi et.al. validated and leveraged Fluent solver and numerical schemes for pressure velocity coupling for natural convection heat transfer on extended vertical base plate in [5]. Enchao et.al. studied natural convection behavior change of heat transfer coefficient with changes in vent opening sizes and numbers as shown in literature [6]. Rudra et.al. extensively studied radiation effects for a free convection flow near a vertical plate with ramped wall temperature [7]. The study shows that radiation influences the velocity field, temperature field, skin effect and Nusselt number.

II. MODELING APPROACH

Low voltage switchgear assemblies consist of three main compartments: at the rear side, compact copper busbars transport large amounts of current within the

cabinet. This current is then distributed to a column of withdrawable units located at the front left hand side. Each drawer is filled with e.g. motor protection devices of various sizes representing the second source of heat generation. Finally the wires coming from the protection units are gathered in a cable compartment being the third source of heat generation in panel as shown in Fig. 2. Detailed modeling of such a multi-scale system results in millions of mesh elements and an excessively long computation time to solve the CFD model. Simplifying the complicated geometry without losing its characteristics is necessary to minimize the solution time. In order to reliably reduce the mesh count and solving time, four main simplifications are applied. Firstly, only the major heat-generating parts have been modeled, namely the busbars, the protection devices and the heaters located in the cable compartment. Additional wires, screws and busbar connection pieces have not been modeled as their contribution to heat dissipation is comparatively negligible. Secondly, the dividing plates between withdrawable units are removed, keeping only the two top dividing plates as the second drawer turned out to be the most temperature-critical one during thermal tests. Thirdly, the protection devices and heaters are simplified and modeled as compact elements with basic geometrical shapes. Finally, the numerous ventilation holes are gathered and simplified by slits while maintaining the same surface area. The study is carried out for two types of switchgear assemblies: one with an hermetic enclosure and the other one with a ventilated enclosure. The model simplifications of internal components and ventilation openings are shown in Fig.2 and Fig.3. Internal organization of components is identical for both enclosure types.

A. Thermal management of hermetic switchgear assemblies

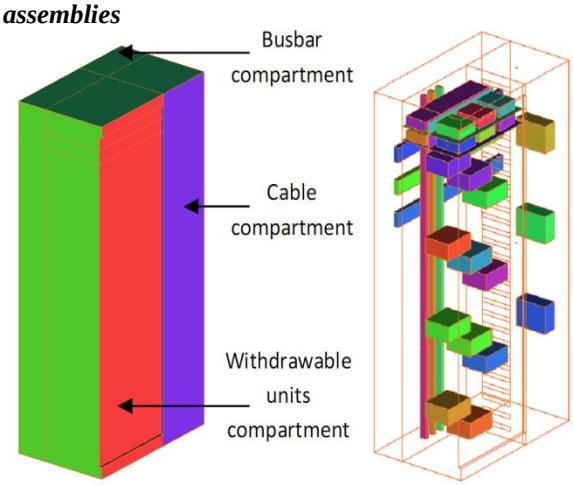


Fig. 2. Modelisation of the hermetic enclosure

This type of enclosure has hermetic walls preventing contamination from any particle size. No air exchange between internal and atmospheric air is allowed. The cooling of such a switchgear assemblies completely depends on internal natural convection and radiation. Within the enclosure, heat is transmitted on one hand via convection of heated air, on the other hand via radiation from solid heaters to the walls of the cabinet. Heat is then conducted through the thickness of the wall from the inner surface to the outer surface, before being transferred to the atmosphere by natural convection and radiation.

B. Thermal management of ventilated switchgear assemblies

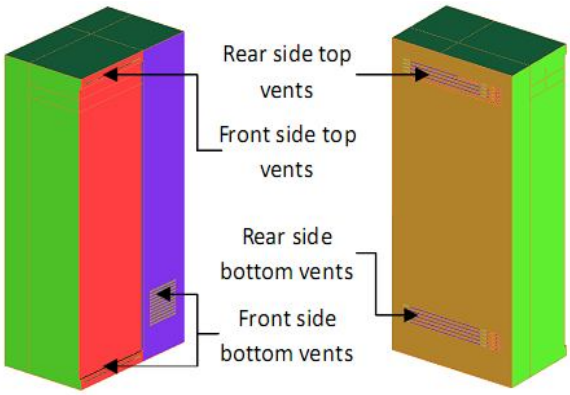


Fig. 3. Modelisation of the ventilated enclosure

This type of enclosure has vent openings allowing air exchange to the atmosphere. The size of vent openings is defined by the ingress protection rating requirements. The cooling of this system is also based on natural convection emphasized by the presence of vent openings and on radiation.

II. COMPUTATIONAL DOMAIN AND DISCRETIZATION

A. Computational Domain

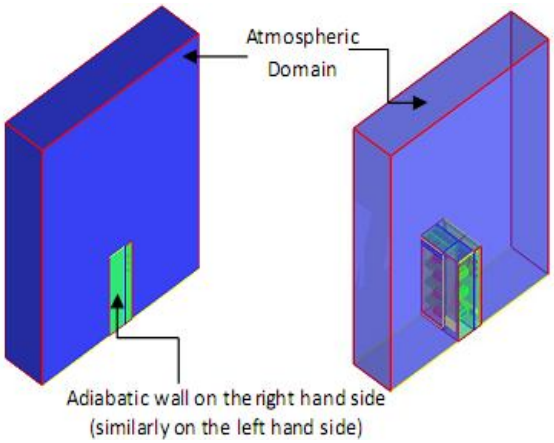


Fig. 4. Computational domain of switchgear assembly

An atmospheric domain is modeled to evaluate heat transfer distribution on the walls of the enclosure. Its size must be big enough to consider the variation of the heat transfer rate on the walls and to avoid air recirculation. The control volume chosen has a size of twice the height of the cabinet above the top wall and three times the width of cabinet starting from front and rear walls.

B. Discretization

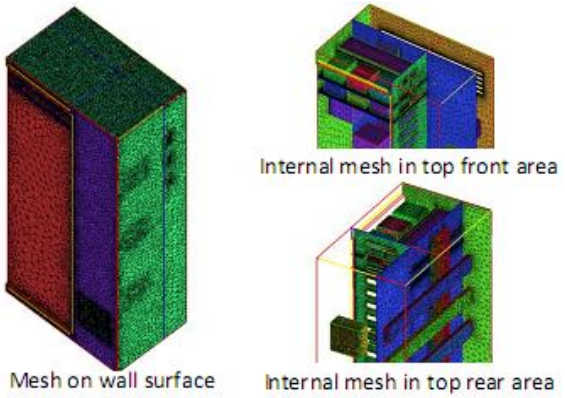


Fig.5. Tetrahedral mesh for the switchgear assembly model, approx. 10 million elements

The computational domain is divided into a certain number of volumetric cells using Ansys ICEM CFD preprocessing tool. Tetrahedral elements are used to discretize the control volume while prism layers are used to capture no-slip-effect on the walls. Small air passages between walls and heat sources or between dividing plates and heat sources with critical temperature and velocity gradients are modeled with finer meshes. The computational domain is discretized with an optimized mesh of approximately 10 million cells and an aspect ratio quality with prism on walls smaller than 50.

III. NUMERICAL MODEL AND BOUNDARY CONDITIONS

A. Conservation Equations

The computational fluid dynamic (CFD) model is based on finite volume method [8]. Navier-Stokes equations for transport of mass, momentum, and energy are used to calculate laminar flow with heat transfer as follows.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{v}) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla P + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \qquad (2)$$

$$\frac{\partial(\rho C_p T)}{\partial t} + \nabla.(\rho C_p T\vec{v}) = \nabla.k\nabla T + H \qquad (3)$$

Equation (1) is the general form of the mass conservation equation valid for incompressible and compressible flows where ρ is the density (amount of mass per unit volume) and $\vec{v}$ is the velocity.

Equation (2) is the momentum equation where P is the static pressure, $\bar{\bar{\tau}}$ is the stress tensor and $\rho\vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces.

Equation (3) is the energy equation where C_p is the specific heat capacity at constant pressure, T is the temperature and k is the thermal conductivity. H represents the sum of all source terms.

B. Radiation Model

A surface-to-surface radiation model is used to account for the radiation exchange between all surfaces contained in the enclosure. The energy exchanged between two surfaces depends on their size, distance and orientation. These parameters are expressed in a geometric function called "view factor", shown in equation (4).

$$F_{ij} = \frac{1}{A_i}\int_{A_i}\int_{A_j}\frac{\cos\theta_i\cos\theta_j}{\pi r^2}\delta_{ij}dA_i dA_j \qquad (4)$$

where the view factor F_{ij} is the fraction of energy leaving surface i incident on surface j, (A_i, A_j) are the areas of surfaces (i, j) respectively, (θ_i, θ_j) are the angles of normal radiation of surfaces (i, j) respectively. δ_{ij} = 1 if the surface j is visible to the surface i, otherwise δ_{ij} = 0. r is the normal distance between the surfaces (i, j).

The amount of incident energy upon a surface from another surface is a direct function of the surface-to-surface view factor. The view factor is the fraction of energy leaving the surface k incident on the surface j. The incident energy flux can be expressed in terms of the energy flux leaving all other surfaces as expressed in equation (5) below.

$$J_k = E_k + R_k\sum_{j=1}^{N} F_{kj}J_j \qquad (5)$$

where J_k represents the energy that is given off by the surface k (also called radiosity), E_k is the emissive power of surface k, R_k is the reflectivity of surface k and N is the number of surfaces.

Governing equations are solved in steady state condition to capture conduction, convection and radiation. Surface-to-surface radiation model is used to calculate the radiative interaction between components, enclosure and atmosphere. Pressure and velocity coupling is modeled with SIMPLE scheme while node-to-node solution method is used for gradient calculation and PESTRO for pressure correction. Momentum and energy are solved with the second order upwind scheme.

C. Shell Conduction

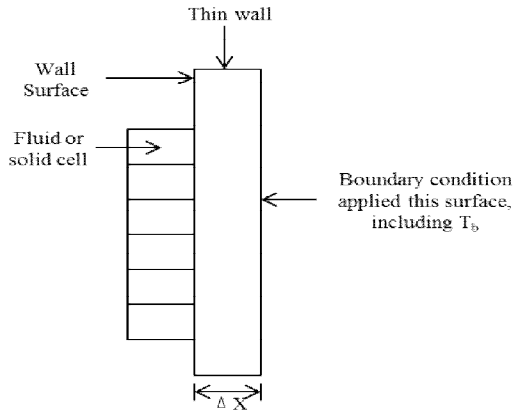


Fig.6. Schematic for shell conduction applied to walls with thin thickness

Low voltage switchgear assemblies contain several parts of thin metal sheets (2mm) such as walls and dividing plates between the withdrawable units.

Meshing these metal sheets with large surface area and small thickness results in a tremendous number of cells. To overcome this challenge, shell conduction model is applied in Fluent. Thin walls are replaced by 2D surfaces while 3D wall effect is incorporated within the numerical model. The thermal resistance $\Delta X / k$ of the 3D wall is specified in the numerical model, where ΔX is the thickness of the wall, k the thermal conductivity of the material and Tb the temperature on the outer surface of the 3D wall as shown in Fig.6.

D. Adiabatic Wall

In practice, switchgear assemblies are used in series and placed side-to-side. In this case, no heat transfer through side walls is possible. To represent this configuration during the experimental tests, side walls are thermally isolated. To model this thermal isolation in the simulation model, adiabatic boundary condition is applied to side-walls.

E. Heat Load and Material Properties

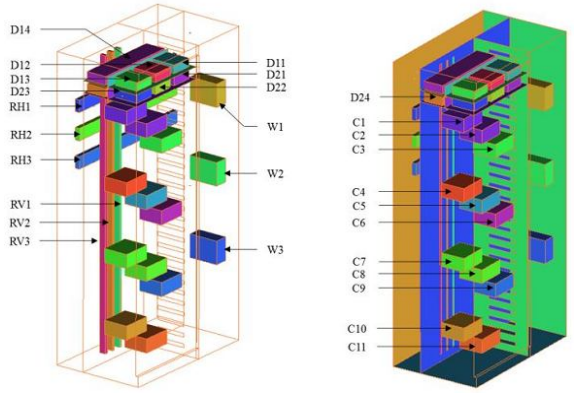


Fig.7. Nomenclature of internal components

The internal details of low voltage switchgear assemblies are shown in fig. 7. Internal components organization is identical for both types of switchgears while heat loads are different. Heat load details of the components are mentioned in Table I.

TABLE I. HEAT LOADS

Component Name	Material	Heat load per component for switchgear assembly with closed air path (W)	Heat load per component for switchgear assembly with open air path (W)
RV1, RV2, RV3	Copper	21.7	33.3
RH1, RH2, RH3	Copper	35.0	60.0
W1, W2, W3	GF25	31.0	44.0
C1, C2, C3, C4, C4, C5, C6, C7, C8, C9, C10, C11	GF25	21.0	30.0
D12	GF25	1.9	1.3
D22	GF25	1.9	1.3
D11, D12, D13	GF25	2.6	1.0
D21, D22, D23	GF25	2.6	1.0

The enclosure is made of steel carbon while some of the internal components are made of copper and GF25 plastic material. The front door of the switchgear is made of ABS plastic material. Emissivity is used to model radiation. The details of material properties are mentioned in Table II.

TABLE II. MATERIAL PROPERTIES

Material Properties	Materials			
	Steel Carbon	*ABS*	*GF25*	*Copper*
Thermal conductivity (W/m K)	43	0.17	0.47	390
Density (kg/m3)	7850	1055	1590	8940
Specific heat capacity (J/kg K)	420	1300	1200	390
Emissivity	0.23	0.9	0.9	0.023

IV. EXPERIMENTAL THERMOCOUPLE LOCATIONS

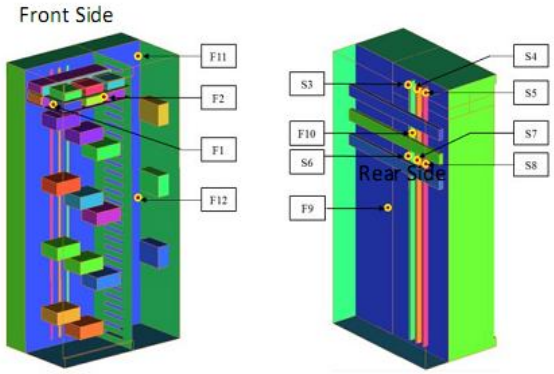


Fig.8. Thermocouple location

Temperature values measured during experimental tests are used to validate the numerical results. Several thermocouples are placed both in the air and on the surface of the components at critical locations to track the temperature in the cabinet. Thermocouple location is shown in fig.8. Thermocouples named F1, F2, F9, F10, F11, F12 are used to measure fluid temperature at sensitive locations while S3, S4, S5, S6, S7, S8 are used to measure surface temperatures. For both cases, ambient temperatures have been specified in accordance with thermal test conditions.

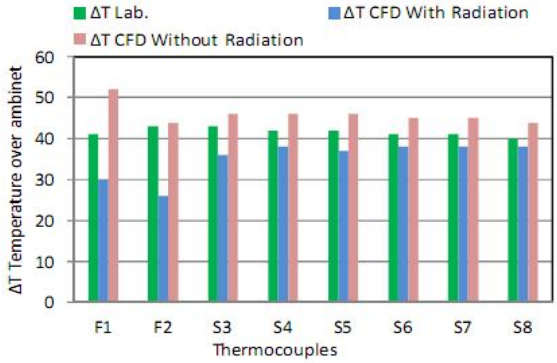
V. RESULTS AND OBSERVATIONS

Both types of switchgear assembly models have been evaluated using Fluent solver and the numerical schemes discussed above. In order to be consistent in comparing experimental and numerical temperature results, temperature values are read at identical co-ordinate locations as thermocouple placements for validation. To compare the temperatures regardless the unit (Kelvin or Celsius), and regardless the ambient temperature of a specific testing day, the difference between measured ambient temperature is used for comparison. This number is called ΔT in the following.

A. Impact of Radiation

The impact of radiation is evaluated for ventilated

enclosures. Two CFD cases, with and without radiation, with similar boundary conditions, are simulated. Computed and experimental temperatures at height point location on solid surface and in the air are compared in graph 1. Temperatures predicted by CFD with radiation are lower than experimental values whereas temperatures predicted by CFD without radiation are higher than experimental data. This behavior is easily explained by the fact that when not modeling radiation, the actual heat transfer rate is reduced, resulting in higher temperatures within the cabinet. For both CFD models, the average difference between experimental and computed temperatures is 5 degrees.



Graph 1. Comparison of experimental data with radiation and no-radiation CFD models in ventilated switchgear

B. Thermal management of hermetic switchgear

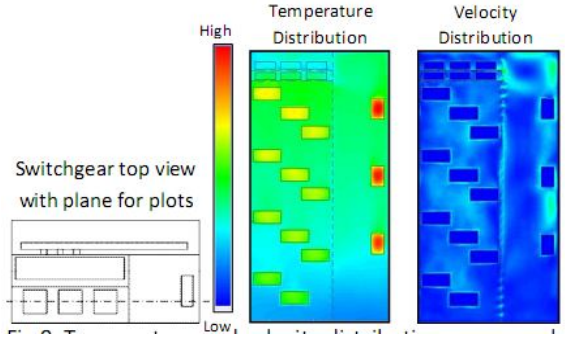
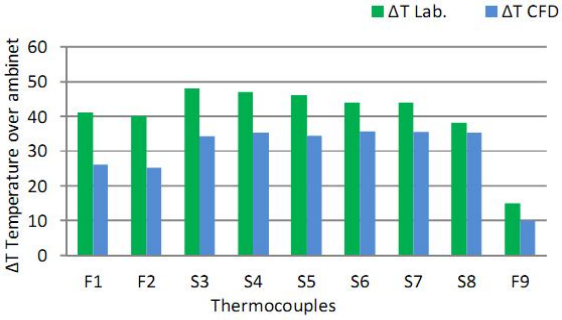


Fig.9. Temperature and velocity distribution on same plane in hermetic switchgear

Switchgear assemblies with hermetic enclosures have a constant volume of air. The components generate heat transmitted on one hand by convection to the surrounding air, on the other hand by radiation to the surfaces of other components and to the walls of the enclosure. Due to the difference of air temperature created within the cabinet, internal air moves according to buoyancy effect : as internal air is heated, warm air with lower density rises. A temperature gradient is established from top to bottom. Hot air tends to accumulate at the top of the enclosure and in particular within the second top drawer as highlighted during previous thermal tests, as shown in fig. 9. Accumulated heat is transferred to the walls first then to the atmosphere via radiation and convection. High velocities are developed near hot components.

A comparison between experimental and numerical temperatures at twelve point location in the air and on solid surfaces is shown in graph 2. CFD under-predicts the temperature by 10 degrees in average. One possible reason for this temperature gap are the emissivity values. Larger emissivity values result in higher radiative transfer to the exterior, therefore to lower temperatures.



Graph 2. Comparison between numerical and experimental data in hermetic switchgear

C. Thermal management of ventilated switchgear

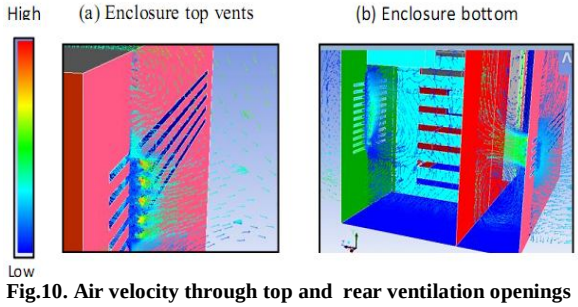


Fig.10. Air velocity through top and rear ventilation openings in ventilated switchgear

Switchgear assemblies with ventilated enclosures have ventilation openings allowing air exchange between the internal air and the atmosphere. Similarly to hermetic switchgear assemblies, natural convection inside the cabinet is driven by buoyancy effect. As hot air with low density rises to the top of the enclosure, the pressure increases at the top of the cabinet, pushing the internal air outside through top ventilation openings as shown in “Fig 10 (a)”. This ascendant movement creates a low-pressure region at the bottom, inducing the entrance of atmospheric air through bottom ventilation openings as shown in “Fig. 10(b)”. This air loop continues until reaching a steady state. In parallel, another part of internal heat is transferred to the exterior by radiation and convection.

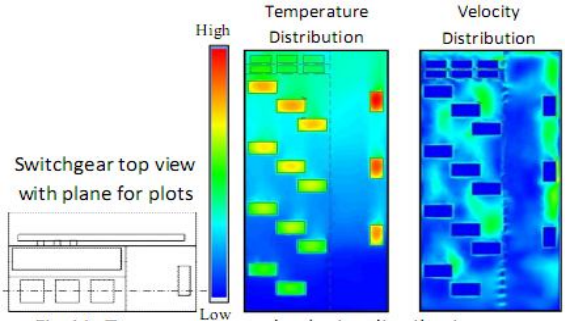
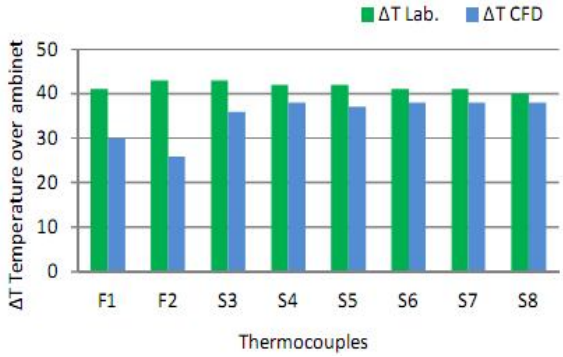


Fig.11. Temperature and velocity distribution on same plane in ventilated switchgear

The interaction between internal and atmospheric air results in a lower air temperature gradient inside the enclosure, compared to the hermetic switchgear. Higher air velocities are developed within the panel as shown in Fig.11.



Graph 3. Comparison between numerical and experimental data in ventilated switchgear

A comparison between experimental and numerical temperatures is shown in Graph 3. The radiation model under-predicts the temperature by 6 degrees in average. One possible reason for this variation are the emissivity values. As explained previously, lower emissivity values result in higher radiation from the components to the walls and from the walls to the exterior, and therefore to lower temperatures than reality.

CONCLUSION

Computational Fluid Dynamics (CFD) is used to evaluate the thermal performance of low voltage switchgear assemblies. Radiation and thermal flow have been simulated. It can be concluded that :

1) Radiation model tends to under-predict the temperature within the cabinet. This can be explained by larger emissivity values than actual values, allowing a higher radiative heat transfer, and therefore a better cooling.

2) Radiation model gives results closer to experimental temperatures in ventilated enclosures more than in hermetic enclosure.

3) Numerical and experimental data are relatively close. The difference mainly comes from manipulation uncertainties during thermal tests, material properties values, such as radiation emissivity, and modeling simplification of components and of internal structure.

4) Overall, the model built for ventilated and hermetic switchgear enclosures, can be used for a large variety of switchgear assembly systems.

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